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**CREW RADIATION DOSE FROM THE PLUME OF A HIGH IMPULSE GAS-CORE
NUCLEAR ROCKET DURING A MARS MISSION**

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TECHNICAL PAPER proposed for presentation at
Second Symposium on Uranium Plasmas: Research and Applications sponsored
by the American Institute of Aeronautics and Astronautics
Atlanta, Georgia, November 15-17, 1971

CREW RADIATION DOSE FROM THE PLUME OF A HIGH IMPULSE GAS-CORE NUCLEAR ROCKET DURING A MARS MISSION

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Abstract

Analytical calculations are performed to determine the radiation dose rate and total dose to the crew of a gas-core nuclear rocket from the fission fragments located throughout the plume volume. The rocket plume is generated by the products of the reactor and consists of hydrogen, uranium, and fission fragments. The mission chosen is a manned "courier" trip to the planet Mars. With the recent radiator-cooled concept of the gas-core nuclear rocket, round trip times to Mars can be as small as 80 days, starting with less than one million kilograms in Earth orbit. These fast trip times require a large number of megawatt hours of energy, and crew radiation dose is a function of the energy required for a mission. Four round trip times were picked in which the system was optimized so the initial vehicle mass in Earth orbit was minimized for each trip time. They are 80, 100, 150, and 200 days. The corresponding Earth orbit initial vehicle masses are 0.94, 0.64, 0.38, and 0.31 million kilograms. The radiation dose from the plume fission fragments to two crew locations of 100 and 200 meters from the nozzle exit are calculated. The doses are calculated assuming that there is a vacuum in the space between the crew and plume.

For the most probable fission fragment retention time in the reactor of 100 seconds, the unshielded radiation dose to a crew located 100 meters from the nozzle exit varies from 170 rem for the 80 day round trip to 38 rem for the 200 day round trip. For a fission fragment retention time of 10 seconds the crew radiation dose varies from 1670 rem for the 80 day trip to 380 rem for the 200 day trip. For a retention time of 1000 seconds the radiation dose decreases to 12 and 2.7 rem for the 80 and 200 day trips respectively.

In the case of the most probable fission fragment retention time of 100 seconds, the crew must be protected from the radiation dose. Five centimeters of lead shielding would reduce the radiation dose by two orders of magnitude thereby protecting the crew. The increase in vehicle weight would be insignificant, for example, a shield of five centimeters thickness and four meters in diameter would add 7120 kilograms to the vehicle gross weight of 0.94 million kilograms. Also additional attenuation is available in the form of liquid hydrogen propellant, spacecraft structure, nuclear fuel, equipment, and stores.

Introduction

In the open-cycle gas-core nuclear rocket concept the heat source is fissioning uranium gas. This released heat is radiated to and absorbed by the hydrogen propellant. The heated propellant is exhausted through a nozzle, producing thrust. The fission fragments that are formed and the unfissioned uranium fuel are also exhausted into the vacuum of space. As the plume is formed, the crew is exposed to gamma radiation from the fission frag-

ments in the plume.

With a recently improved version of the gas-core nuclear rocket engine concept, Fig. 1,^(1,2) additional specific impulse is obtained by using a vapor-fin space radiator to dispose of waste heat not regeneratively removed by the hydrogen propellant in the moderator.

The radiation dose to the crew from the fission fragments in the plume can be separated into two components. Component one results from the fact that there is a microscopic amount of plume material that has sufficient kinetic energy to flow back towards the vehicle. Some of this material will strike and stick to the vehicle. Since this material will contain fission fragments, these gamma radiation sources will stay with the crew throughout the entire trip and this dose could represent a significant source of radiation. Masser⁽³⁾ has estimated this dose and has concluded it would be less than 10^{-3} rem for a typical manned Mars mission.

Component two of the dose results from the fission fragment distribution throughout the entire plume volume and is potentially much larger than component one. Since the plume contains over 99 percent of the exhausted material, 99 percent of the fission fragments will be in the plume. It is the purpose of this paper to estimate the radiation dose rate and total dose to the crew from the fission fragments in the plume for four specific missions to the planet Mars.

Another source of radiation is caused by the delayed decay of the fission fragments that are passing through the nozzle. This includes delayed neutrons which can cause secondary fissioning and gamma's. This source, however, has not been included. There is another radiation source associated with the gas-core reactor, that of the reactor core. This radiation source, along with solar radiation, must be ultimately considered when total dose rates to the crew are evaluated. This study, however, is concerned only with that part of the total radiation problem that arises from the fission fragments in the plume volume.

Selected Mission Characteristics

The mission selected for the analysis of the plume radiation hazard is a manned "courier" trip to Mars.⁽⁴⁾ The trip involves leaving a 600 kilometer circular orbit around Earth with a trans Mars injection maneuver, a high ellipse orbit insertion maneuver at the planet Mars, a trans Earth injection maneuver, and a circular orbit insertion maneuver upon return to Earth. It is possible with the radiatively cooled open-cycle gas core nuclear rocket to achieve this total trip in as little time as 75-80 days. Figure 2 shows the variation of this trip time with the initial mass in Earth orbit needed to accomplish the trip. Four trip times were selected on this curve to calculate the plume radiation dose associated with each trip. They

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were 80, 100, 150, and 200 days.

Rocket Engine Characteristics

For each mission time the system was optimized in order to minimize the initial vehicle mass in Earth orbit. Therefore for each mission there is a specific engine with its own characteristics. This results in a given thrust and specific impulse. Table 1 lists several characteristics of the engine for each of the chosen missions.

In the case of each engine, the hydrogen chamber exit enthalpy is diluted by cold hydrogen used to transpiration cool the nozzle; therefore one can calculate a specific impulse with and without nozzle cooling. The exit-to-chamber pressure ratio is assumed to be 10^{-5} and Patch⁽⁵⁾ has calculated the exit parameters needed for the calculation of radiation from the plume. Table 2 summarizes the exit parameters needed for the calculations for each of the missions.

Calculation of Fission Fragment Formation

The number of fission fragments formed is calculated using Eq. (2.49) of Glasstone and Sesonski.⁽⁶⁾

$$\text{Reactor Power (Watts)} = \frac{\text{Fissions Per Second}}{3.1 \times 10^{10}} \quad (1)$$

Since the reactor powers and engine running times are known from table 1, the number of fission fragments produced are known. It is also assumed the average molecular weight of the fission fragments is 117.5 or half of the molecular weight of the U_{235} fuel. In addition, it is assumed that the number fraction of fission fragments in any unit volume is constant throughout the plume.

Calculation of Plume Density

In order to calculate the number of fission fragments at any point within the plume volume, the density throughout the plume must be known. It has been shown in nozzle plume flows that the mass flux, ρV , varies inversely as the square of the distance from the source point. Hill and Draper⁽⁷⁾ have shown the density in a plume can be closely approximated by

$\rho =$

$$\frac{4\rho_e M_e B}{\left(1 + \frac{\gamma-1}{2} M_e^2\right)^{1/2} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2} \left(\frac{r_e}{r}\right)^2 e^{-\lambda^2(1-\cos\theta)^2}} \quad (2)$$

Where the coordinates r and θ are shown in Fig. 3; ρ is the density at any point in the plume; ρ_e is exit density; M_e is exit Mach number; γ is the ratio of specific heats; and B and λ are constants.

Also from Hill and Draper⁽⁷⁾ we have

$$B = \frac{\lambda}{4\sqrt{\pi}} \left(\frac{\gamma-1}{\gamma+1}\right)^{1/2} \left(\frac{2}{\gamma+1}\right)^{1/(\gamma-1)} \quad (3)$$

$$\lambda = \frac{1}{\sqrt{\pi} \left(1 - \frac{C_F}{C_{Fmax}}\right)} \quad (4)$$

Where C_F and C_{Fmax} are thrust coefficients and are evaluated using Eqs. (4.33) and (4.34) of Shapiro.⁽⁸⁾

Radiation Dose to the Crew

The radiation dose to the crew is calculated using the basic equation from Glasstone and Sesonski.⁽⁶⁾

$$\text{Radiation Dose Rate (rem/hr cm}^3\text{)} = 5.2 \times 10^3 \frac{C}{\vec{L} \cdot \vec{L}} \quad (5)$$

Where C is the source strength at the point $P_{r,\theta,\phi}$ in the plume in curies per unit volume, E is the photon energy in MeV, and \vec{L} is the vector distance in centimeters from the point $P_{r,\theta,\phi}$ to the crew.

The energy release of U_{235} fission fragments, $F(t)$, varies from approximately 0.07 MeV per fission per second at 10 seconds after fission to 0.00002 MeV at 10000 seconds after fission.⁽⁹⁾ The number density of fissions at point $P_{r,\theta,\phi}$ is given by

$$\text{Number Density of Fissions at } P_{r,\theta,\phi} = \frac{1}{2} \frac{\rho A_0 P_{FF}}{m} \quad (6)$$

Where ρ is the density at point $P_{r,\theta,\phi}$, A_0 is Avogadro's number, P_{FF} is the number fraction of fission fragments at point $P_{r,\theta,\phi}$ and m is the molecular weight of the nozzle exit gas.

The value of L as shown in Fig. 4 is given by

$$\vec{L} \cdot \vec{L} = z^2 + 2zr \cos \theta + r^2 \quad (7)$$

Where z is the distance from the crew to the exit plane of the nozzle. Combining the energy release of decay for the fission fragments and Eqs. (5) and (6), and using the identity that one curie equals 3.7×10^{10} disintegrations per second.

Radiation Dose Rate per unit volume from $P_{r,\theta,\phi}$ in rem per hour per cm^3 is,

$$\text{Radiation Dose Rate (rem/hr cm}^3\text{)} = \frac{5.2 \times 10^3 F(t)}{3.7 \times 10^{10}} \frac{1}{\vec{L} \cdot \vec{L}} \left(\frac{1}{2} \frac{\rho A_0 P_{FF}}{m}\right) \quad (8)$$

The number fraction of fission fragments (P_{FF}) at point $P_{r,\theta,\phi}$ is given by

$$P_{FF} = \frac{(R)(m)}{\dot{m}_{H_2} A_0} 6.2 \times 10^{13} \quad (9)$$

Where the reactor power, R , is given in megawatts, and the hydrogen flow rate, \dot{m}_{H_2} , is given in kilograms per second. Combining Eqs. (7), (8), and (9)

Radiation Dose Rate (rem/hr cm³)

$$= \frac{(5.2)(F(t)) 10^6}{3.7(z^2 + 2zr \cos \theta + r^2)} \left[\frac{(R)(\rho)3.1}{\dot{a}_{H_2}} \right] \quad (10)$$

The total Radiation Dose in rem per hour is

$$\int_{r=r_e}^{r'} \int_{\theta=0}^{\pi/2} \int_{\phi=0}^{2\pi} (\text{constant}) \frac{e^{-\lambda^2(1-\cos\theta)^2}}{(z^2+2zr\cos\theta+r^2)} \sin\theta d\phi d\theta dr \quad (11)$$

Where the constant is equal to

Constant

$$= \frac{F(t)(R)(5.2)(3.1)(10^6)(4)\rho_e M_e Br_e^2}{(\dot{a}_{H_2})(3.7)\left(1 + \frac{r-1}{2} M_e^2\right)^{1/2} \left(\frac{2}{r+1}\right)^{(r+1)/2(r-1)}} \quad (12)$$

After the integration on ϕ is performed one has

Radiation Dose Rate $\left(\frac{\text{rem}}{\text{hr}}\right)$

$$= 2\pi(\text{constant}) \int_{r=r_e}^{r'} \int_{\theta=0}^{\pi/2} \frac{e^{-\lambda^2(1-\cos\theta)^2}}{(z^2+2zr\cos\theta+r^2)} \sin\theta d\theta dr \quad (13)$$

The integration of r is stopped at r' whenever an increase of r' by a factor of ten does not increase the radiation dose rate more than 1 percent. The resultant value of r' was 100 kilometers. Since the plume expands at a rate of over 50 kilometers per second, the transient conditions at engine start up and shut down were ignored.

Discussion of Results

The radiation dose rate and total dose from the fission fragments in the plume to the crew is calculated for two crew locations - that of 100 meters and 200 meters from the nozzle exit. In order to better understand the radiation hazard of the plume, one must analyze which part of the plume is most hazardous. Figure 5 shows the percentage of the radiation dose received by the crew as more of the plume is included in the dose calculation. If we include only the first 0.1 kilometer of the plume, only 50 percent of the radiation dose is received from this volume. When one includes 1.0 kilometer of the plume, over 90 percent of the radiation dose is included. At a distance of 10.0 kilometers, 99 percent of the radiation dose is included. And at a distance of 100.0 kilometers from the nozzle, essentially 100 percent of the gamma radiation dose to the crew is included.

Another variable of importance is the retention time of the fission fragments in the reactor core. The longer they stay in the reactor, the less of a radiation source they are to the crew. Retention times varied in the analysis from 10 to 10 000 seconds. The large range used for the fission fragment retention times are based on the

flow system itself. The average retention time of a uranium atom is calculated to be 1000 seconds, and the average retention time of a hydrogen atom is 10 seconds. From this and fluid dynamic considerations, 100 seconds appears to be a reasonable retention time for the fission fragments.

The results of the radiation dose rate for the engine associated with each mission is shown on Fig. 6. Only the crew nozzle separation distance of 100 meters is shown in this figure. One can see that the dose rate falls as retention time of the fission fragments increases from 10 to 10,000 seconds. For the 80 day round trip, the dose rate falls from approximately 23. rem per hour for a fission fragment retention time of 10 seconds, to less than 0.007 rem per hour for a retention time of 10 000 seconds. Also as the trip time increases, the dose rate falls. However, there is almost no drop in dose rate between the 100 and 200 day round trip. This is because the engine powers are almost identical (see tables 1 and 2). Figure 7 shows the effect of crew nozzle separation distance on radiation dose rate for the 80 day round trip. The dose rates are just about half if the crew is 200 meters forward of the nozzle exit instead of 100 meters.

A more important factor than dose rate is the total dose and whether this poses a hazard. In Fig. 8, one can see the results of the total dose to the crew for the various round trip times to Mars. Again it must be stressed that this is an unshielded case; no attenuation effect is taken into account. For the 80 day round trip time, the radiation dose is as high as 1670. rem for a fission fragment retention time of 10 seconds. The radiation dose, however, drops rapidly with increasing retention time; at 10 000 seconds the radiation dose is only 0.5 rem. As the trip time increases, less energy is required and the crew dose decreases. For the 200 day round trip, the total dose for fission fragment retention times of 10 and 10 000 seconds are only 380. and 0.1 rem respectively.

At the most probable retention time of 100 seconds, the radiation dose varies from 170 rem to 38 rem for the 80 and 200 day round trip time respectively. In this case the crew must be protected from the radiation dose. Five centimeters of lead shielding would reduce the radiation dose by two orders of magnitude thereby protecting the crew. The increase in vehicle weight would be insignificant. For example, a shield of five centimeters thickness and four meters in diameter would add 7120 kilograms to the vehicle gross weight of 0.94 million kilograms. The equivalent attenuation of 5 centimeters of lead is also provided by 7.3 meters of liquid hydrogen. The amount of liquid hydrogen that is necessary for the 80 day and 200 day trips is 9500 and 2300 cubic meters respectively. This is equivalent to a tank that is 10 meters in diameter and 121 meters long for the 80 day trip, or one that is 10 meters in diameter and 29.3 meters long for the 200 day trip. Therefore, sufficient attenuation by this liquid hydrogen is possible during the initial portion of the trip. Also additional attenuation is available in the form of spacecraft structure, nuclear fuel, equipment and stores.

Figure 9 shows the effect of crew distance

from the nozzle exit on total radiation dose. Again the total dose appears to be just about half if the crew is located 200 meters from the nozzle instead of 100 meters.

The energy required for this trip to Mars varies with trip time. Figure 10 shows the effect of total radiation dose received during the trip as a function of total energy needed for the trip. One can see as the energy needed for a particular trip time is increased, the crew dose increases. In fact, for the trip times included in this analysis the total radiation dose is proportional to the energy required for the mission. Therefore, within the ranges used in this analysis one can estimate the crew radiation dose by knowing the energy needed for the mission.

Summary of Results

Calculations were performed to determine the radiation dose rate and total dose to the crew of a gas-core nuclear rocket from the fission fragments located throughout the plume volume. Calculations were carried out for round trip times to the planet Mars of 80, 100, 150, and 200 days. Crew distances from the nozzle exit were assumed to be either 100 or 200 meters. Fission fragment retention times in the reactor were assumed to vary from 10 to 10 000 seconds. The radiation dose from the plume was calculated assuming no shielding material existed between the crew and the total plume volume. The following results were obtained:

1. For the most probable fission fragment retention time of 100 seconds, and crew nozzle separation of 100 meters, the radiation dose varied from 170. to 38. rem for the 80 and 200 day round trip times respectively. Five centimeters of lead shielding would reduce the radiation dose by two orders of magnitude, thereby protecting the crew. The increase in vehicle weight would be insignificant. For example, a shield of five centimeters thickness and four meters in diameter would add 7120 kilograms to the vehicle gross weight of 0.94 million kilograms. Also additional attenuation is available in the form of liquid hydrogen propellant, spacecraft structure, nuclear fuel, equipment, and stores.

2. For the trip times included in this analysis the total radiation dose to the crew is proportional to the energy required for the mission. Therefore, within the ranges used in this analysis one can estimate the crew radiation dose by knowing the energy needed for the mission.

3. For the crew-nozzle separation of 100 meters, approximately 50 percent of the plume radiation is received from the first 0.1 kilometer into the plume. This percentage is increased to 90 percent for 1 kilometer and 100 percent for 100 kilometers into the plume.

4. For an 80 day round trip to Mars, with a crew-nozzle separation distance of 100 meters, the radiation dose varied from about 0.5 to 1670. rem for fission fragment retention times of 10 000 and 10 seconds, respectively.

5. For all cases, increasing the crew distance from 100 to 200 meters from the nozzle exit reduced the unshielded radiation dose by half.

Appendix - Symbols

A_0	Avogadro's number
B	defined by Eq. (3)
C	source strength in Curies per unit volume
C_F	thrust coefficient
$C_{F_{max}}$	maximum thrust coefficient
E	photon energy in MeV
$F(t)$	fission fragment energy release as a function of time after fission
\vec{L}	vector distance from point $P_{r,\theta,\phi}$ to the crew
M	Mach number
m	molecular weight
P_{FF}	number fraction of fission fragments at point $P_{r,\theta,\phi}$
R	reactor power
r,θ,ϕ	spherical coordinates
V	mean velocity of particles in plume
z	distance from crew to nozzle exit
γ	ratio of specific heats
λ	defined by Eq. (4)
ρ	mass density
Subscript:	
e	nozzle exit

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	Mars round trip time (days)			
	80	100	150	200
Thrust (lb)	28900	19380	18200	17150
Specific impulse (sec)	5180	4840	4800	4750
Reactor power (MW)	4520	2830	2640	2460
I.M.E.O.* (kg)	0.94×10^6	0.84×10^6	0.38×10^6	0.31×10^6
H ₂ mass (kg)	0.662×10^6	0.428×10^6	0.220×10^6	0.164×10^6
Engine running time (hr)	72.7	65.4	35.9	27.8

*Initial mass in earth orbit.

TABLE 1 MISSION CHARACTERISTICS FOR THE FOUR MARS ROUND TRIP TIMES CHOSEN FOR THE ANALYSIS

	Mars round trip time (days)			
	80	100	150	200
Chamber temperature, (°K)	29760	27680	27430	27170
Chamber pressure, (atm)	1000	1000	1000	1000
Exit temperature, (°K)	3310	3160	3150	3135
Exit Mach no., M _e	10.03	9.96	9.93	9.90
Exit velocity, V _e , (M/S)	5.52×10^4	5.15×10^4	5.11×10^4	5.06×10^4
Exit molecular wt, m _e	2.00	2.01	2.01	2.01
Ratio of specific heats, γ _e	1.255	1.263	1.263	1.263

TABLE 2 GAS-CORE ENGINE CHARACTERISTICS FOR THE FOUR MARS ROUND TRIP TIMES CHOSEN FOR THE ANALYSIS

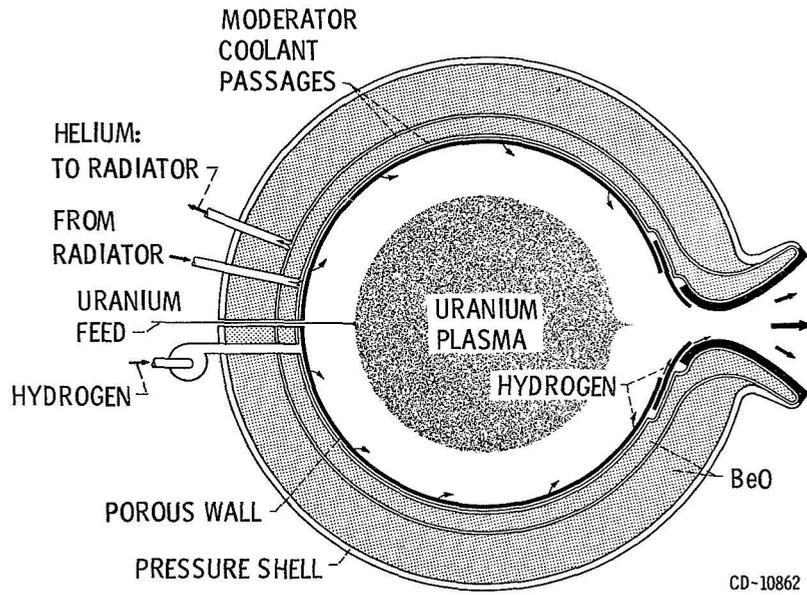


Figure 1. - Porous wall gas core engine concept.

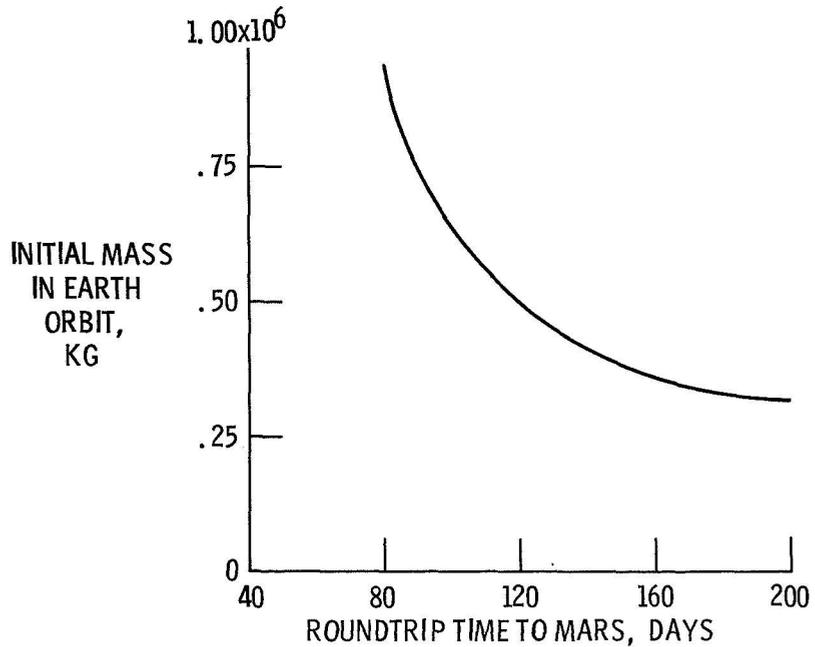


Figure 2. - Effect of round trip time to Mars on the minimum initial mass in Earth orbit needed for the mission.

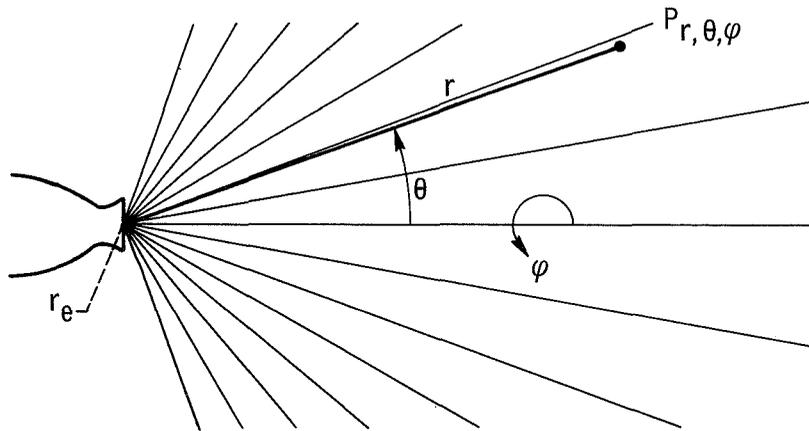


Figure 3. - Spherical coordinate system used in analysis.

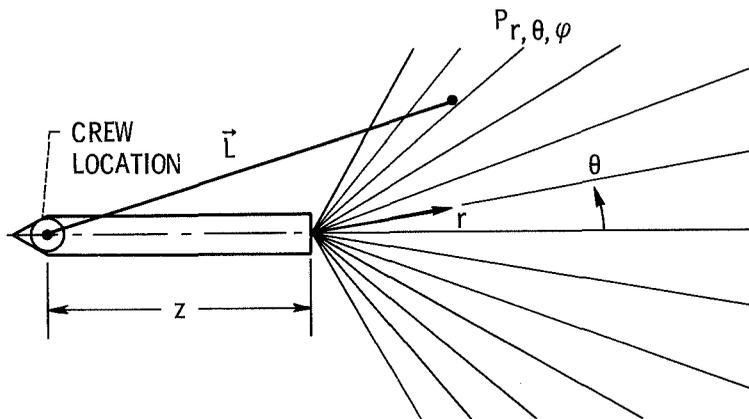


Figure 4. - Relationship between point $P_{r, \theta, \phi}$, the distance to the crew, \vec{L} , and the location of the crew from the nozzle exit, z .

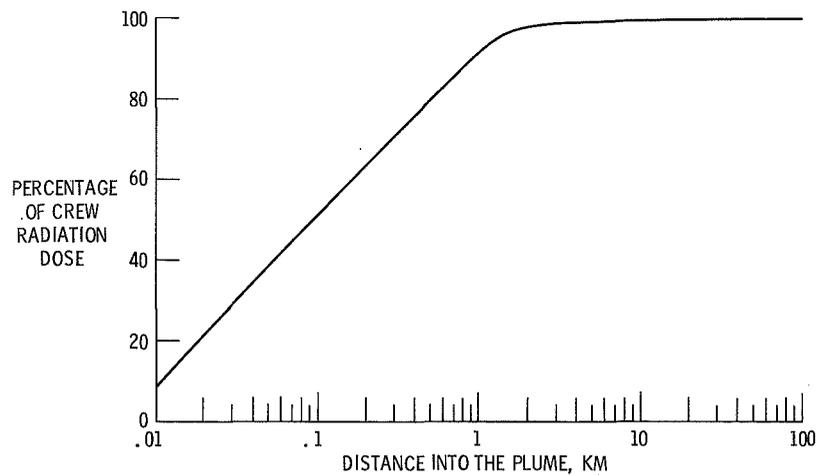


Figure 5. - Increase of crew radiation dose as a function of integrated distance into the plume.

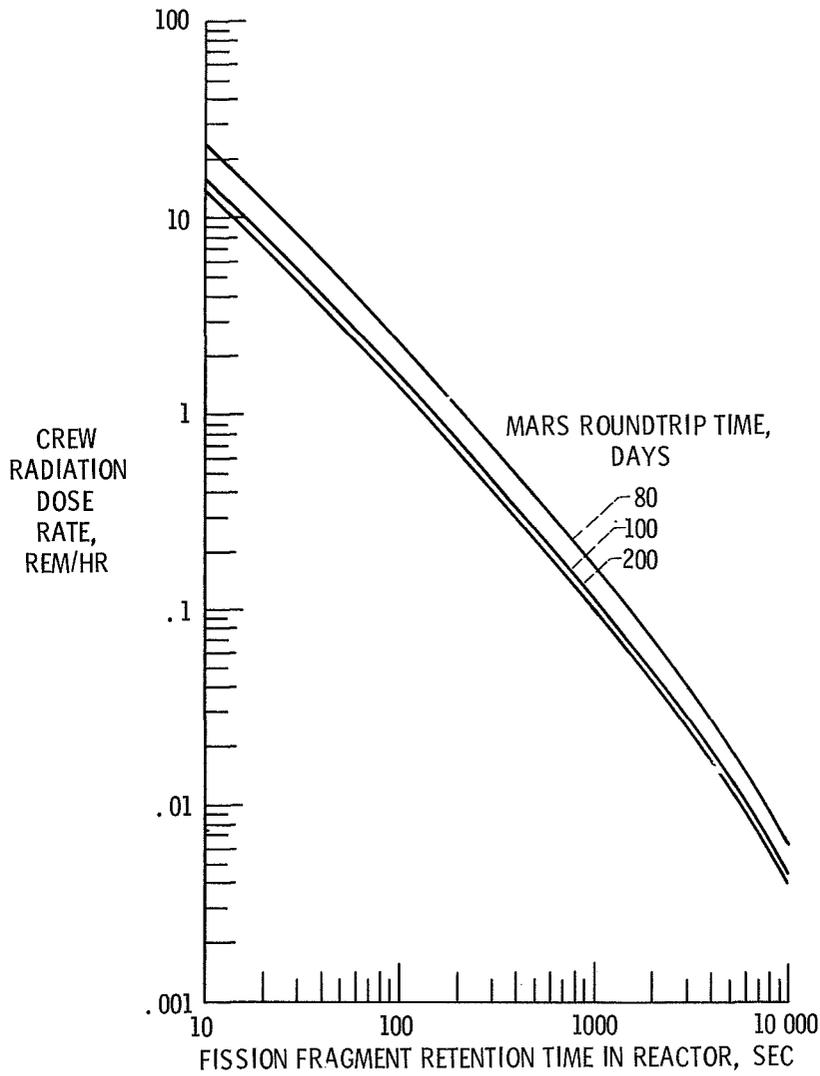


Figure 6. - Effect of fission fragment retention time in reactor on the crew radiation dose rate. Crew-nozzle separation is 100 meters.

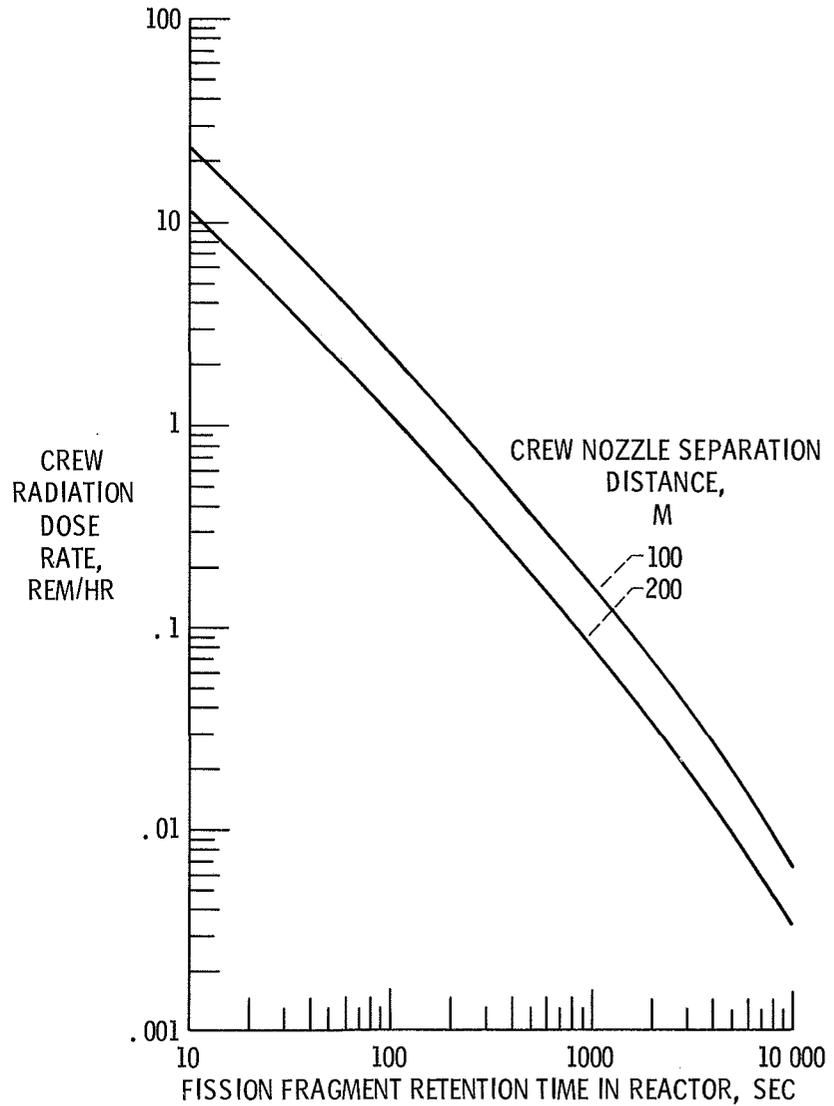


Figure 7. - Effect of fission fragment retention time in reactor on the crew radiation dose rate. Mars round trip time is 80 days.

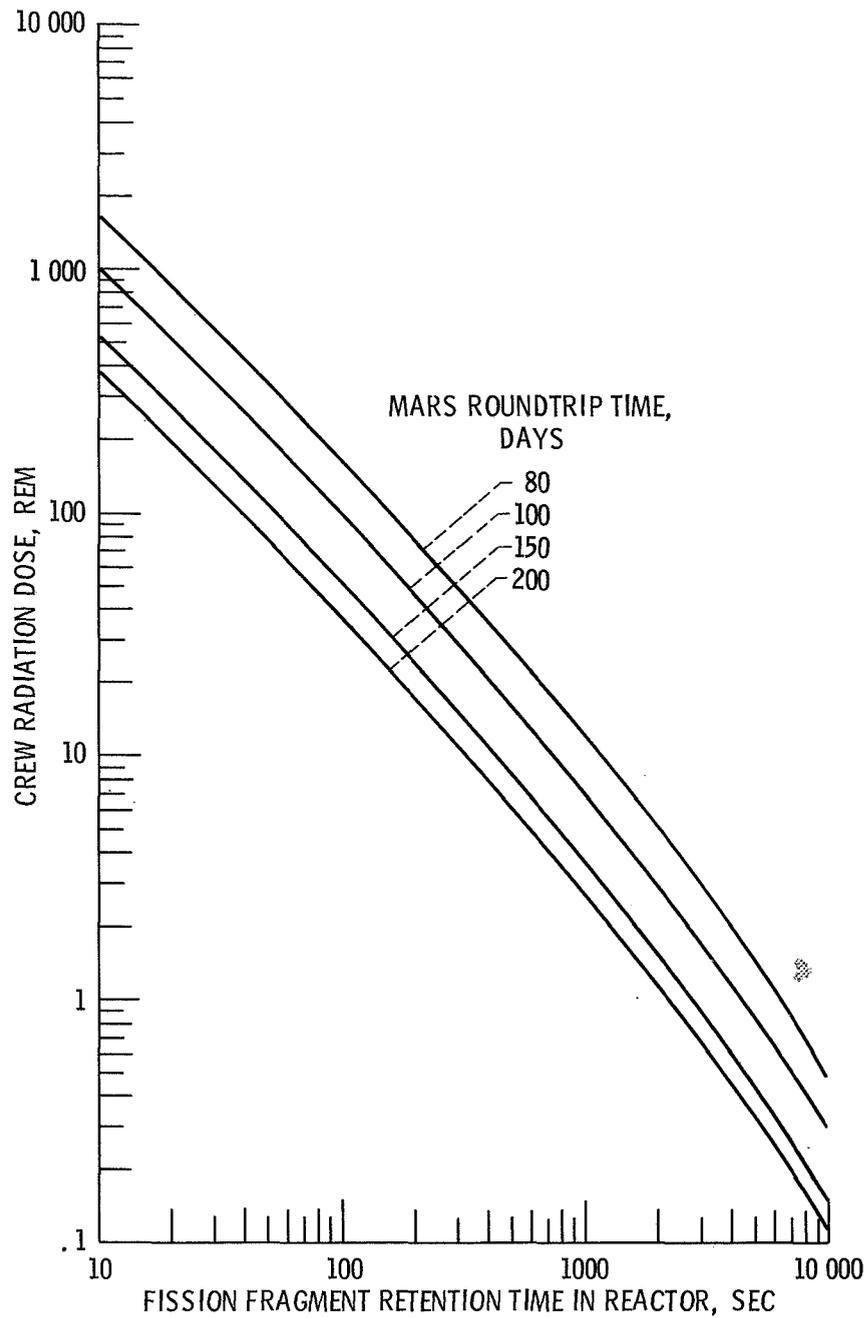


Figure 8. - Effect of fission fragment retention time in reactor on the total crew radiation dose. Crew nozzle separation is 100 meters.

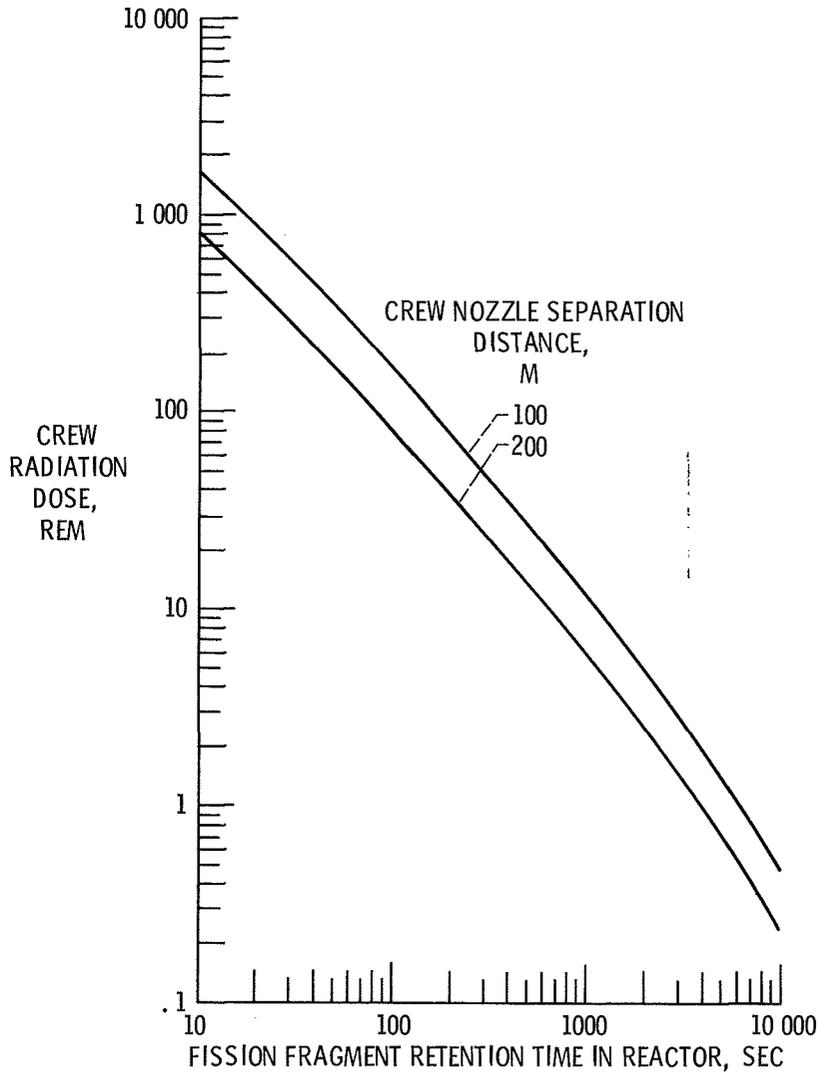


Figure 9. - Effect of fission fragment retention time in reactor on the crew total radiation dose. Mars round trip time is 80 days.

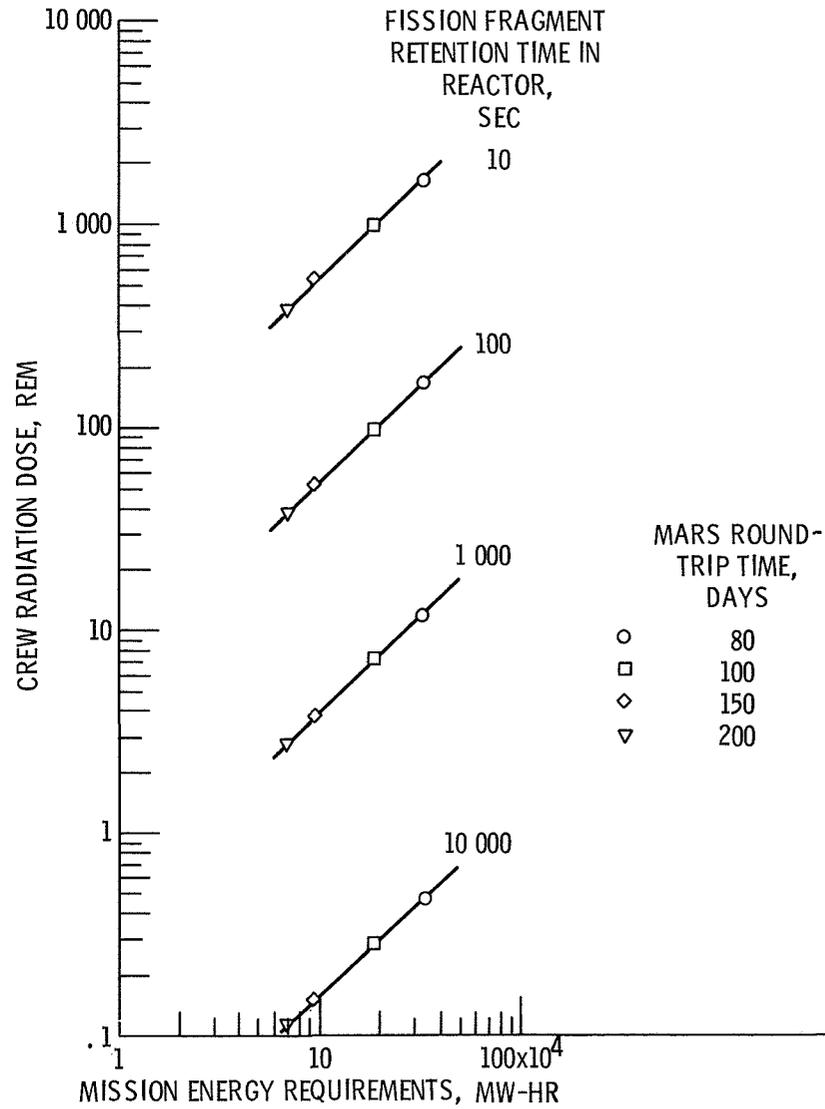


Figure 10. - Effect of mission energy requirements on the crew radiation dose. Crew nozzle separation is 100 meters.